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Ecological operation for Three Gorges Reservoir

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Abstract: The traditional operation of the Three Gorges Reservoir has mainly focused on water for flood control, power generation, navigation, water supply, and recreation, and given less attention to the negative impacts of reservoir operation on the river ecosystem. In order to reduce the negative influence of reservoir operation, ecological operation of the reservoir should be studied with a focus on maintaining a healthy river ecosystem. This study considered ecological operation targets, including maintaining the river environmental flow and protecting the spawning and reproduction of the Chinese sturgeon and four major Chinese carps. Using flow data from 1900 to 2006 at the Yichang gauging station as the control station data for the Yangtze River, the minimal and optimal river environmental flows were analyzed, and eco-hydrological targets for the Chinese sturgeon and four major Chinese carps in the Yangtze River were calculated. This paper proposes a reservoir ecological operation model, which comprehensively considers flood control, power generation, navigation, and the ecological environment. Three typical periods, wet, normal, and dry years, were selected, and the particle swarm optimization algorithm was used to analyze the model. The results show that ecological operation modes have different effects on the economic benefit of the hydropower station, and the reservoir ecological operation model can simulate the flood pulse for the requirements of spawning of the Chinese sturgeon and four major Chinese carps. According to the results, by adopting a suitable re-operation scheme, the hydropower benefit of the reservoir will not decrease dramatically while the ecological demand is met. The results provide a reference for designing reasonable operation schemes for the Three Gorges Reservoir.

Key words: *ecological operation; environmental flow; Three Gorges Reservoir; particle swarm optimization algorithm*

1 Introduction

Reservoirs can be used to generate hydroelectric power, supply water, and provide recreational opportunities. They play an important role in promoting social and economic development. However, adverse environmental impacts of reservoirs have also been identified. Damming of the world's rivers has come at great cost to their ecological health and ecosystem

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services valued by the society (Postel and Richter 2003; Richter and Thomas 2007). Reservoirs have considerable influence on downstream river ecosystems (WCD 2000; Richter and Thomas 2007). Ecological impacts of reservoirs include inhibiting migratory animals like anadromous fishes, causing eutrophication by plankton blooming, decreasing flow volumes in tail waters, stabilizing flow regimes by reducing peak flows, changing thermal regimes, altering river beds, and increasing substrate grain size by trapping sediment. Reservoir operation influences river flow regimes, which, in turn, influence river ecosystem health (Bednarek and Hart 2005; Jager and Smith 2008). Healthy river ecosystems provide ecosystem services, including water supply, water reclamation, pollution abatement, and groundwater recharge.

We envision that in the future, holistic management strategies for reservoir projects will be designed to maximize both ecological benefits and those associated with energy production. In contrast, conventional reservoir management strategies typically optimize energy and economic benefits, and address ecosystem values only as the constraints on reservoir release and elevations (Jager and Smith 2008). Typical objectives are to minimize water deficits or to maximize hydropower production, revenue, or profit (Chaves et al. 2003; Kerachian and Karamouz 2007). To reduce the influence of reservoir construction on river ecological systems and the natural water environment, possibly one of the most valid strategies is modification of reservoir operation, hereafter referred to as ecological operation, for maintaining the natural flow regimes and associated ecosystem health and services (Symphorian et al. 2003; Richter and Thomas 2007; Halleraker et al. 2007; Shiau and Wu 2007).

The Three Gorges Project, due to its enormous power generation capacity and the fact that hydropower is considered a form of clean energy, plays an indispensable role in China’s energy conservation and emission reduction strategy (Cao et al. 2007). It brings huge benefits in flood control, power generation, and navigation improvement. However, the impoundment of the Three Gorges Reservoir has also altered the hydrological regime of the Yangtze River to some degree, causing changes in the frequency, magnitude and duration of floods, water temperature, discharge, water level, and sediment concentration, and, as a consequence, the structure and function of biological communities associated with the Yangtze River ecosystem have been affected (Xia et al. 2005). Therefore, maximizing both ecological benefits and those associated with energy production has become an urgent issue. In order to reduce the negative influence of reservoir operation, ecological operation of the reservoir should be studied to maintain healthy river ecosystems. This study considered ecological operation targets, including maintaining the river environmental flow and protecting the spawning and reproduction of the Chinese sturgeon and four major Chinese carps. This paper proposes a reservoir ecological operation model that comprehensively considers flood control, power generation, navigation, and the ecological environment. Three typical periods, wet, normal, and dry years, were selected, and particle swarm optimization was used to analyze the model.

2 Methods and materials

2.1 Study area

The Yangtze River is the largest river in China and ranks third in the world in terms of its length and the mean annual volume of water flowing into the East China Sea. Fig. 1 shows a diagram of the Yangtze River. Because of its large catchment area and water volume, the Yangtze River has remarkable features, such as its diversified utilization of water resources and the controlling role of its geographical position in regional climate change. Its water resources, accounting for 36% of China's total, are 9.619×10^{11} m^3, of which 99% is surface water. The hydropower resources in the Yangtze River Basin are abundant too. Partly estimated, 45 694 reservoirs with a total storage capacity of 1.586×10^{11} m^3 have been built on the upper main course and tributaries of the Yangtze River, and, of these reservoirs, 134 large-scale ones had a total storage capacity of 1.064×10^{11} m^3 by the end of the year 2000.

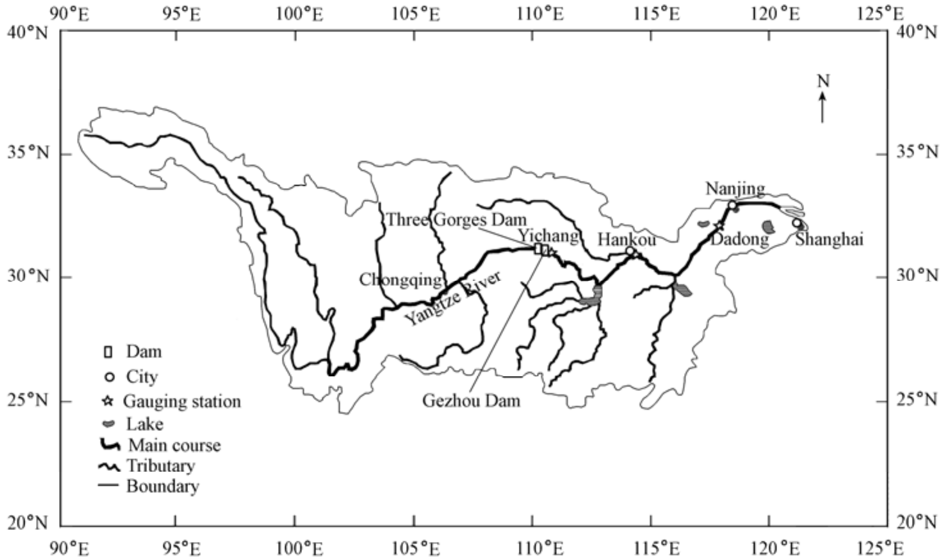

Fig. 1 Diagram of Yangtze River

The Three Gorges Reservoir, with a huge storage capacity of 3.93×10^{10} m^3, is located at the upper end of the Yangtze River, just 44 km upstream from the Yichang gauging station (CWRC 1997). Its installed capacity and annual electricity generation are 18 200 MW and 8.47×10^{10} kWh, respectively. The rated power of the Three Gorges station is 4 990 MW, and the minimum and maximum releases are 1 580 and 98 800 m^3/s, respectively. The output coefficient of the Three Gorges power station is 8.5. Table 1 shows the basic parameters of the Three Gorges Reservoir. The reservoir serves multiple purposes of flood control, irrigation, navigation, and power production (Guo and Wang 2010).

The regulation of the Three Gorges Project is designed such that the reservoir is normally maintained at the flood control limit level of 145 m and operated to store or release flood water based on the flood control regulation options in the event of a large flood in the flood season from middle June to late September. The reservoir is uniformly impounded from 145 m to 175 m in October and maintained at 175 m in November. If the inflow cannot meet the needs for guaranteed output of the power station afterwards, the reservoir draws down gradually to 155 m by the end of May and to 145 m by June 10.

Table 1 Characteristic water levels and storage volumes of Three Gorges Reservoir

Case	Water level (m)	Storage volume (10^{10} m^3)
Normal regulation	175.0	3.930
Flood control regulation	145.0	1.715
Dry season regulation	155.0	2.280

After the Three Gorges Reservoir was impounded, many new issues regarding the river environment had to be faced. First, the temperature of the water released from the reservoir was significantly lower than the natural water temperature from late April to early May due to water temperature stratification, which caused about a 10- to 20-day delay in spawning time for four major Chinese carps below the reservoir. Second, the reduction of peak flow released from the reservoir affected the fish spawning and reproduction below the reservoir due to the reservoir operation for power generation. Third, in some cases the released water caused gas bubble disease in fish, particularly in the fry, due to over-saturation of nitrogen. Besides, eutrophication and algal bloom may occur in the reservoir due to low flow and poor water quality. These are the adverse impacts of the Three Gorges Reservoir on the aquatic production in the Yangtze River, and they should be eliminated or alleviated as much as possible by various measures. The negative impacts of the reservoir have attracted special attention of the government and researchers.

2.2 Targets of ecological operation for Three Gorges Reservoir

2.2.1 Environmental flow target recommendation for Yangtze River below reservoir

Environmental flow is a part of the original river flow that should continue to flow down the channel in order to maintain a healthy river ecosystem. The river ecosystem is seen as all components of the landscape directly linked to the river and the life forms (King et al. 1999). The river environmental flow can be classified as minimal environmental flow and optimal environmental flow. The minimal environmental flow is the basic flow that maintains the survival of river aquatic organisms. Under the minimal environmental flow condition, the damage to the stream ecosystem cannot be rectified. The optimal environmental flow is the flow that maintains the stability and biodiversity of the river ecosystem. Now there are numerous methods of assessment of environmental flow worldwide. These methods can be classified as hydrological methods, hydraulic rating methods, habitat simulation methods, and holistic methods. A monthly frequency computation method, one of the hydrological methods, was provided for computation of minimal and optimal environmental flows in this study. First, the dry (with a hydrological frequency $p < 25\%$), normal ($25\% < p < 75\%$), and wet ($p > 75\%$) years are identified based on the yearly average flow series. Second, the minimal environmental flow recommendation is set as the 90%-frequency monthly flow and the optimal flow recommendation is set as the 75%-frequency monthly flow.

The Yichang gauging station is the control point of the upper Yangtze River Basin and is located at the starting point of the middle Yangtze River, 44 km below the Three Gorges Dam. Based on monthly flow data from 1900 to 2006 from the Yichang gauging station, the minimal and optimal river environmental flows were analyzed. Table 2 shows the results of environmental flow recommendations below the Three Gorges Reservoir.

Table 2 Environmental flow recommendations below reservoir (m^3/s)

Typical year	Environmental flow	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Dry	Minimum	3 627	3 184	3 240	4 760	8 220	12 191	20 200	17 566	13 643	11 676	7 235	4 882
	Optimal	3 841	3 410	3 811	5 508	9 391	13 800	22 200	19 845	17 800	13 731	8 227	5 050
Normal	Minimum	3 804	3 427	3 430	4 844	8 270	13 400	23 497	21 700	19 500	15 384	8 423	5 254
	Optimal	3 990	3 590	3 720	5 441	9 230	15 037	26 123	22 968	22 173	17 184	9 250	5 530
Wet	Minimum	3 905	3 474	3 590	5 508	9 480	16 147	27 300	23 800	23 400	15 000	8 999	5 673
	Optimal	4 200	3 836	3 956	6 680	11 500	17 600	29 800	28 000	28 400	20 400	10 400	5 966

2.2.2 Ecological operation targets for fish spawning below reservoir

The Chinese sturgeon is one of the first-class nationally protected animals in China. The Chinese sturgeon has established a new spawning ground with a length less than 7 km in the main stream of the Yangtze River below the Gezhouba Dam due to the construction of the dam (Wei 2003). The spawning time is October and November each year. The spawning of the Chinese sturgeon requires special hydrological and hydraulic conditions, which directly affect spawning quantity and quality. The Three Gorges Reservoir was impounded in October, reducing the released flow from the reservoir. The reduction of flow directly or indirectly affects the spawning and reproduction. In order to protect the Chinese sturgeon, eco-hydrological targets were determined for ecological operation for the Three Gorges Reservoir. The hydrological indicators include discharge, water level, water temperature, sediment concentration, flow rate, flow recession rate, and water level recession rate, which were calculated with the average value ± the standard deviation. The eco-hydrological targets for spawning grounds for the Chinese sturgeon (Table 3) were calculated according to the hydrological conditions during the spawning periods of the Chinese sturgeon below the Three Gorges Reservoir.

The four major carps, black carp, grass carp, silver carp, and variegated carp, are traditionally major economic fishes. Proper water temperature and flow conditions are essential for their natural spawning. Normally, from April to July they migrate to the main course of the Yangtze River or its tributaries for breeding, and their spawning is directly related to the river water temperature, flow rates, flow velocity, and their variations. When the river water temperature falls within the range of 18℃ to 26℃, and the water level is rising over a sufficiently long period, it can promote fish migration, sexual maturity, mating, and spawning. According to investigation, there are 30 spawning grounds in the section from Chongqing to Jiujiang, of which 11 grounds are upstream of Yichang (Li 2001). This study was concerned mainly with May and June, which is the main spawning period of the four major Chinese carps in the middle reach of the Yangtze River. The discharge process can be considered one discharge rising event when the discharge has risen for three consecutive days or more. Based on this definition, relevant annual parameters such as the number and duration of discharge rising events during May to June were calculated. The hydrological indicators include discharge, water level, water temperature, sediment concentration, flush times, flush duration, flow rising rate, and water level rising rate, which were also calculated with the average value ± the standard deviation. The eco-hydrological targets for the spawning grounds for the four major Chinese carps (Table 4) were calculated according to the hydrological conditions during the spawning periods of the carps below the Three Gorges Reservoir.

Table 3 Eco-hydrological targets for spawning grounds for Chinese sturgeon in October and November

Month	Item	Discharge (m^3/s)	Water level (m)	Water temperature (℃)	Sediment concentration (kg/m^3)	Flow rate (m/s)	Flow recession rate ($m^3/(s·d)$)	Water level recession rate (m/d)
October	Mean	17 410	45.30	20.0	0.60	1.50	306	0.09
	Range	10 500-22 026	42.58-46.77	18.9-21.5	0.31-0.93	1.35-1.80	39-710	0.02-0.21
	Target	14 534-20 286	44.18-46.38	19.2-20.8	0.45-0.75	1.40-1.65	132-480	0.04-0.14
November	Mean	9 767	41.80	16.7	0.21	1.00	179	0.07
	Range	6 918-12 637	39.95-44.09	15.6-17.6	0.06-0.40	0.80-1.30	65-356	0.04-0.14
	Target	8 064-11 470	40.57-42.97	16.1-17.3	0.12-0.30	0.90-1.20	105-253	0.04-0.10

Table 4 Eco-hydrological targets for spawning grounds for four major Chinese carps in May and June

Month	Item	Discharge (m^3/s)	Water level (m)	Water temperature (℃)	Sediment concentration (kg/m^3)	Flush times	Flush duration (d)	Flow rising rate ($m^3/(s·d)$)	Water level rising rate (m/d)
May	Mean	11 209	42.99	21.4	0.33	2.5	5	1 559	0.63
	Range	7 415-16 702	41.25-44.63	20-22.7	0.06-0.81	1-5	2-12	664-2750	0.32-0.95
	Target	8 854-13 564	42.01-43.97	20.66-22.12	0.15-0.51	2-3	3-8	910-2 208	0.41-0.85
June	Mean	18 291	44.85	23.6	0.88	3	5.5	2143	0.57
	Range	11 658-22 600	41.53-46.78	22.7-24.5	0.40-1.94	1-5	3-12	1 006-4 129	0.30-0.98
	Target	15 471-2 111	43.40-46.30	23.04-24.15	0.57-1.19	2-4	3-8	1 355-2 931	0.40-0.74

2.3 Reservoir ecological operation model

The ecological operation for a reservoir is a very complex combinatorial operation problem. Operation and management become more complex and more dynamic due to growing conflicts among the competing objectives, including the water quality, endangered species habitat preservation, and various recreational uses in addition to the traditional objectives of flood control, water supply, navigation, and hydropower production. The ecological operation model mainly includes the objective function, constraints, and optimization algorithm. The maximum hydropower generation is usually the operation objective and other objectives are constraints.

2.3.1 Ecological operation model

2.3.1.1 Objective function

In this study, the objective function was maximizing the hydropower production. The model was formulated for monthly operation, and, mathematically, the objective function was provided by Guo and Wang (2010):

$$\max F = \max \sum_{t=1}^{M} K Q_t H_t \Delta T \tag{1}$$

where F is the hydropower produced during the total period, K is the power coefficient, Q_t is the amount of water released to turbines during period ΔT, H_t is the average head available during period ΔT, and M is the total number of time periods.

2.3.1.2 Constraints

The objective function above of the reservoir optimal operation model is subject to the following constraints:

(1) Mass balance equation for the reservoir storages and inflows:

$$V_{t+1} = V_t + \left(I_t - Q_t - S_t\right)\Delta T \tag{2}$$

where V_{t+1} and V_t are the final and initial storage volumes, respectively, during period ΔT, I_t is the inflow into the reservoir during period ΔT, and S_t is the overflow or spill from the reservoir during period ΔT.

(2) Storage bounds for the reservoir:

$$V_{t\min} \le V_t \le V_{t\max} \tag{3}$$

where $V_{t\min}$ and $V_{t\max}$ are the minimum and maximum storages allowed in period ΔT, respectively. These storages are constrained by flood protection rules during the monsoon season. In the remaining periods, the minimum storage $V_{t\min}$ is considered equal to the dead storage, while the maximum storage $V_{t\max}$ is equivalent to the full capacity of the reservoir.

(3) Turbine capacity constraint:

$$N_{\min} \le N_t \le N_{\max} \tag{4}$$

where $N_{\min}$ and $N_{\max}$ are the minimum and the maximum turbine capacities of the power plant, respectively.

(4) Reservoir release constraint:

$$q_{t\min} \le q_t \le q_{t\max} \tag{5}$$

where the reservoir release q_t is the total release during period ΔT including the hydropower production release and the overflow from the reservoir, and $q_{t\min}$ and $q_{t\max}$ are the minimum and maximum releases during period ΔT, respectively.

(5) Ecological constraint:

The operation model mainly subject to the released flow from the reservoir satisfies the minimum and optimal environmental flow demands as much as possible and provides the flow conditions for fish spawning and reproduction downstream of the reservoir to protect fish populations.

(6) Non-negative constraint:

All values in the ecological operation model are positive.

2.3.2 Particle swarm optimization algorithm

Particle swarm optimization (PSO) is an optimization algorithm based on the community intelligence principle, which was originally proposed by Kennedy and Eberhart (1995). The PSO technique can easily handle the nonlinearity of the problem; the search does not depend on the initial population, and it overcomes problems of local optima that are common in some conventional nonlinear optimization techniques (Salman et al. 2002). The PSO technique has successfully demonstrated numerical optimization and shown itself to be an attractive alternative for global optimization problems.

Each particle has position, velocity, and fitness values decided by an objective function of the problem. The position is a potential solution to the optimization problem. In a D-dimensional search space, the position of particle i is represented as $\boldsymbol{x}_i = \left(x_{i1}, x_{i2}, ..., x_{iD}\right)^{\mathrm{T}}$, the velocity is $\boldsymbol{v}_i = \left(v_{i1}, v_{i2}, ..., v_{iD}\right)^{\mathrm{T}}$, its previous best position is $\boldsymbol{p}_{\mathrm{Best}i} = \left(p_{\mathrm{best}i1}, p_{\mathrm{best}i2}, ..., p_{\mathrm{best}iD}\right)^{\mathrm{T}}$, the best position of the entire population is $\boldsymbol{g}_{\mathrm{Best}} = \left(g_{\mathrm{best}1}, g_{\mathrm{best}2}, ..., g_{\mathrm{best}D}\right)^{\mathrm{T}}$, and particle i updates its velocity and position according to Eqs. (6) and (7):

$$v_{id}^{k+1} = wv_{id}^{k} + c_1 r_1 \left(p_{\mathrm{best}id}^{\ k} - x_{id}^{k}\right) + c_2 r_2 \left(g_{\mathrm{best}d}^{\ k} - x_{id}^{k}\right) \tag{6}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{7}$$

where v_{id}^{k} is the component in dimension d of the ith particle velocity at iteration step k, x_{id}^{k} is the component in dimension d of the ith particle position at iteration step k, c_1 and c_2 are positive constants, r_1 and r_2 are two random functions in the range [0, 1], and w is the inertia weight. A large inertia weight favors a global search, while a small inertia weight favors a local search; usually, it decreases linearly during the iteration of the algorithm. w can be determined by Eq. (8):

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{L_{\max}} \times L \tag{8}$$

where $w_{\max}$ and $w_{\min}$ are the maximum and minimum of w, respectively, $L_{\max}$ is the maximum iteration number, and L is the present iterative number.

3 Results and discussion

According to the ecological operation goals, three typical hydrological years were selected for the simulation and optimization model. The operation results were analyzed.

3.1 Model parameters

To formulate the PSO model for ecological operation for the Three Gorges Reservoir, it is expedient to consider the problem a combinatorial optimization problem.

In the model, model parameters were set as follows: K = 8.5, $V_{t\min}$ = 1.72 × 10^{11} m^3, $V_{t\max}$ = 3.93 × 10^{11} m^3, $N_{\min}$ = 4.99 × 10^6 kW, $N_{\max}$ = 1.82 × 10^6 kW, $q_{t\min}$ = 1580 m^3/s, and $q_{t\max}$ = 9880 m^3/s. The programs of PSO were compiled by Matlab 7.0 software. After many experiments and comparisons, the parameters were adopted as follows: the size of populations were 50; the range of inertia weight was $[w_{\min}, w_{\max}] = [0.4, 0.9]$; c_1 and c_2 were all equal to 2.05; the iterations continued until the iteration number was equal to 500; the random noise of $\boldsymbol{v}_i$ was randomly distributed over the range (0, 1); the velocity threshold was equal to 0.1; and the variation coefficient was equal to 0.7.

The monthly inflow data of the Three Gorges Reservoir from 1900 to 2006 were analyzed, and the initial water level was 145 m. Typical hydrological years were selected to study the ecological operation for the Three Gorges Reservoir: a wet year, 1907, a normal year, 1990, and a dry year, 1978. The monthly inflow data of the three typical years are shown in Table 5.

Table 5 Monthly inflow data of three typical years for Three Gorges Reservoir (m^3/s)

Typical year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1907	3970	4000	3920	6680	8920	16200	29400	32300	38700	33000	12200	6380
1990	4795	4929	5581	6936	15373	20797	28481	22384	24600	19055	10375	5940
1978	4227	3294	3083	4998	10495	24263	25342	23703	20487	12955	9451	5541

In this study, three operation schemes of the reservoir were examined: (1) reservoir operation considering river environmental flow, (2) reservoir operation considering the spawning and reproduction of the Chinese sturgeon, for which the simulation period was September, October, and November, and (3) reservoir operation considering the spawning and reproduction of four major Chinese carps, for which the simulation period was May and June.

3.2 Model results

3.2.1 Reservoir operation results considering river environmental flow

Three typical hydrological years were analyzed in the reservoir optimal model. After 500 iterations, the optimization results were obtained. Table 6 shows the results of reservoir ecological operation in three representative years. Fig. 2 is the comparison of released flow and environmental flow in wet, normal, and dry years.

Table 6 Reservoir ecological operation in three representative years

Typical year	Generation capacity (10^4 kW)	Power generation (10^8 kWh)	Minimal flow (m^3/s)	Abandoned flow (m^3/s)
Wet	13102.6	959.76	5470	16886
Normal	12565.9	919.08	5500	448
Dry	10769.7	787.91	4500	238

According to the operation results, the task of flood control should be considered a priority and the water level remained at 145 m in flood periods.

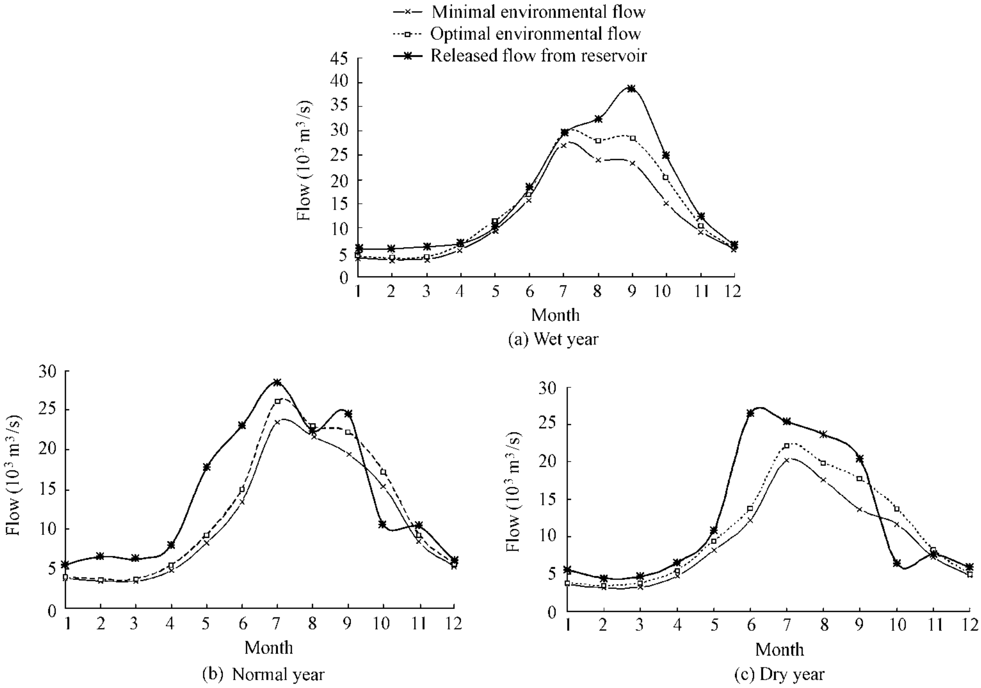

Fig. 2 Operation results in different hydrological years

In the wet year (1907), the guarantee capacity can be satisfied and the minimal and optimal environmental flow demands can be satisfied each month, the influence on power generation is very little due to sufficient inflow to the reservoir mitigating the mismatch between power generation and environmental flow, and the abandoned flow occurs from July to October. In the normal year (1990), the released flow from the reservoir can satisfy the minimal and optimal environmental flow demands except in the storage period of the reservoir (October), the abandoned flow occurs only in July, and the influence on hydropower generation is not significant. In the dry year (1978), the released flow in October cannot satisfy the minimal and optimal environmental flow demands; in November it cannot satisfy the optimal environmental flow demand, but can satisfy the minimal environmental flow demand; in other months it can satisfy the environmental flow demand. Due to the shortage of inflow in February and March, the reservoir cannot satisfy the guaranteed power output limit, the abandoned flow occurs in June, and the influence on the hydropower generation is significant.

3.2.2 Reservoir operation results considering spawning of Chinese sturgeon

Fig. 3 shows the operation results from September to November in wet, normal, and dry years. According to Fig. 3(a), in the wet year, the total power generation of September, October, and November are 3.41×10^{10} kWh; the released flow can provide the required spawning conditions for the Chinese sturgeon and environmental flow. According to Fig. 3(b), in the normal year, the total power generation is 2.49×10^{10} kWh; the released flows in September, October, and November are 24 600, 10 785 and 10 375 m^3/s, respectively, and the released flow in September and November can satisfy river environmental flow demands except in October; and the recession rates of flow in October and November are, respectively, 103 and 203 $m^3/(s \cdot d)$, which can provide the flow recession rate of eco-hydrological targets of the Chinese sturgeon's spawning periods. According to Fig. 3(c), in the dry year, the total power generation is 1.85×10^{10} kWh; the released flows in September, October, and November are 20 487, 6 444, and 7 633 m^3/s, respectively, and the released flow in September and November can satisfy the river environmental flow demands except in October; the water level cannot rise to 175 m; and the recession rates of flow in October and November are, respectively, 93 and 92 $m^3/(s \cdot d)$ which cannot provide the flow recession rate of eco-hydrological targets for the Chinese sturgeon's spawning periods. Finally, the operation measure of impounding water in advance was taken in the dry year in order to minimize the adverse effects on the Chinese sturgeon's spawning.

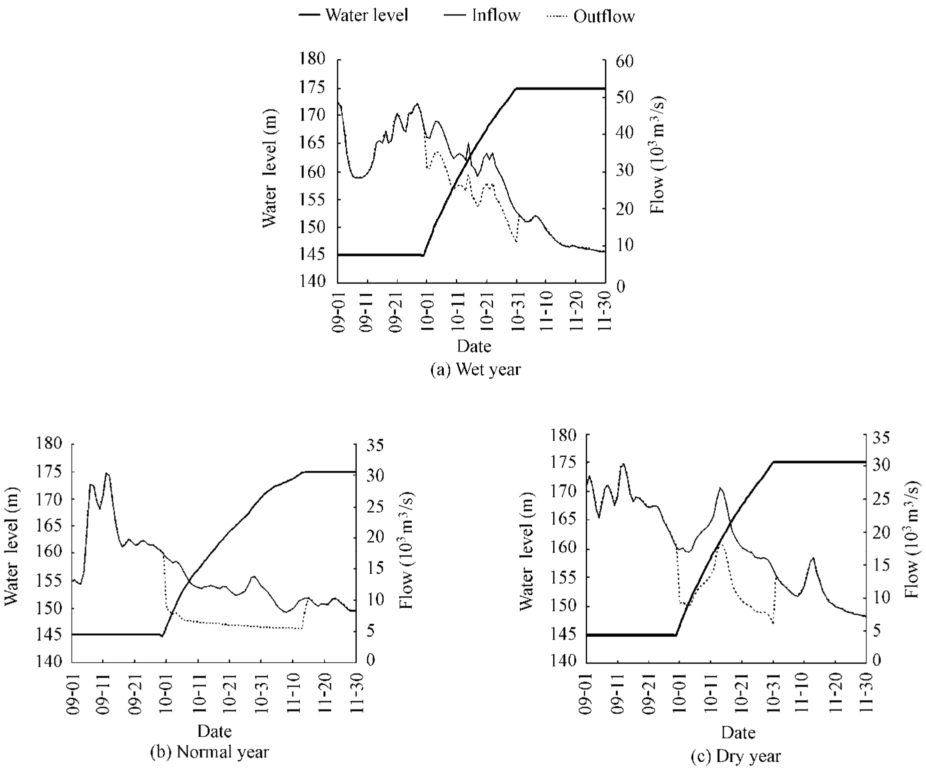

Fig. 3 Operation results from September to November in different hydrological years

3.2.3 Reservoir operation results considering spawning of four major Chinese carps

Fig. 4 shows the operation results from May to June in wet, normal, and dry years.

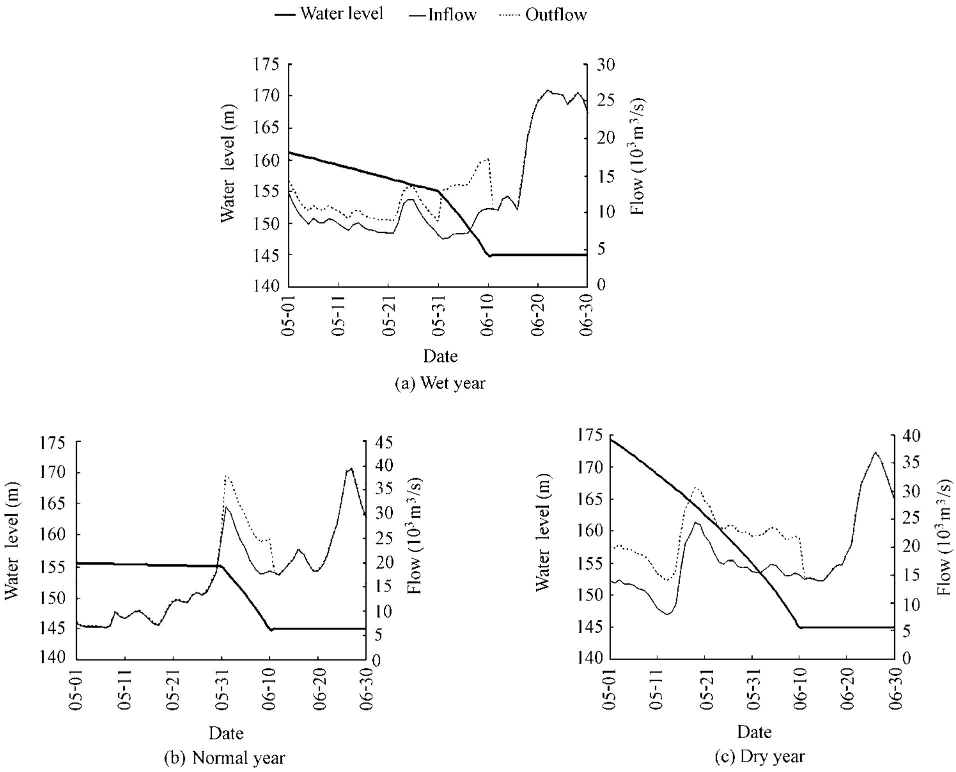

Fig. 4 Operation results from May to June in different hydrological years

According to Fig. 4(a), in the wet year, the total power generations of May and June are 1.50×10^{10} kWh; the released flows in May and June are 10555 and 18379 m^3/s, respectively, and the released flows in May and June can satisfy the river environmental flow demand; and the hydrological conditions of released flow from the reservoir can provide the spawning conditions of four major Chinese carps. According to Fig. 4(b), in the normal year, the total power generation is 2.29×10^{10} kWh; the released flows in May and June are 21533 and 22976 m^3/s, respectively; and the released flows in May and June can satisfy the river environmental flow demand. The flow rising rates in May and June are, respectively, 2 743 and 2091 $m^3/(s{\cdot}d)$, which can satisfy the flow rising rates of eco-hydrological targets for four major Chinese carps' spawning. According to Fig. 4(c), in the dry year, the total power generation is 1.73×10^{10} kWh; the released flows in May and June are 10616 and 26443 m^3/s, respectively, and the released flow can satisfy river environmental flow demands; and the flow rising rates in May and June are, respectively, 1633 and 1938 $m^3/(s{\cdot}d)$, which can meet the eco-hydrological targets for four major Chinese carps' spawning periods.

The operation results show that the measure of a flood pulse can be used to create appropriate flow conditions during the periods of spawning peaks of four major Chinese carps. Therefore, establishing appropriate flood pulse conditions will be beneficial to four major Chinese carps and will not impair the benefit from power generation.

4 Conclusions

In this paper, the ecological operation targets were first provided from the perspectives of maintaining river environmental flow and protecting the spawning of the Chinese sturgeon and four major Chinese carps. In addition, a reservoir ecological operation model was established and a particle swarm optimization algorithm was applied to the operation model. The results show that the minimal and optimal environmental flow demands can be satisfied in wet and normal years, and there are no obvious influences on the power generation; however, in dry years there is an obvious influence on the power generation and the released flow from the reservoir cannot satisfy the environmental flow demands during the periods of impounding water. According to the normal impounding water scheme, the released flow from the reservoir can provide for the spawning of the Chinese sturgeon in wet and normal years but not in dry years. Reservoir ecological operation can simulate a flood pulse for the spawning conditions of the four major Chinese carps. Creating appropriate flood pulse conditions will be beneficial to the ecosystem and will not impair the benefit from power generation. This study provides important information for maintaining healthy river ecosystems. However, ecological operation of the reservoir is very complex. Therefore, more ecological operation issues, such as the water quality of the reservoir, sediment deposition, oxygen saturation, and saltwater intrusion problems, need to be considered in detailed studies.

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